Sensing with Waves: Classical and Quantum

Apoorva D. Patel

Centre for High Energy Physics, Indian Institute of Science, Bangalore
http://iqti.iisc.ac.in/

Horizons in Accelerators, Particle/Nuclear Physics
and Laboratory-based Quantum Sensors for HEP/NP

Discussion Meeting, ICTS, Bengaluru, 16 November 2022

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GPS uses both space and time separations to fix space-time location.

In d dimensions, a simplex has $d+1$ points.

Can multiple receivers on a mobile phone provide extra information?
Can multiple tips of an AFM or STM provide new structural information?

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Large-baseline-interferometry uses spatial correlations in signals to filter out unwanted local disturbances.
Long exposures (with Fourier transform of signals) use temporal correlations to filter out unwanted transients.

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Multi-path signals can arise in other ways too.
Hanbury-Brown–Twiss interferometry uses intensity correlations, with identical quantum particles providing multiple path contributions.

Quantum Algorithms

Quantum dynamics evolves both wave and particle properties of the physical components.

Quantum algorithms exploit both 0-dim and 1-dim structures in the data, by superposition and tensor product (ordered sequence) respectively.

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Classical algorithms can use either wave properties or particle properties. It is instructive to analyse how much can be gained from each separately.

Note: Combining superposition and tensor product produces entanglement.
Wave dynamics alone needs only coherence.

Factorisation

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Examples:

- A digital language with the place value system.
- Binary tree search for looking up a word in a dictionary.
- Any Boolean function can be expressed as a multi-variate linear polynomial, $\prod_{i=1}^{n} x_i + \ldots + \sum_{i=1}^{n} a_i^{(1)} x_i + a^{(0)}$, with $N = 2^n$ terms.

In the factorised form, $\prod_{i=1}^{n}(c_i + x_i)$, it can be evaluated with $O(n)$ effort.

Factorisation can reduce the temporal resources by a factor $(N/\log_2 N)$, which is the maximal gain achievable in "particle-like" implementations.

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Multiple signals can coexist at a single space-time point.

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Examples:

- Electromagnetic wave broadcasts for communications.
- A uniform superposition of $N = 2^n$ components can be created with n qubits and n rotations: $|0\rangle^{\otimes n} \longrightarrow \left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)^{\otimes n} = 2^{-n/2} \sum_{i=0}^{2^n-1} |i\rangle$

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The caveat is that the final measurement destroys the superposition, extracting only $O(n)$ selected properties of the $O(2^n)$ output components (by interference, amplification, or otherwise).

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So the best of both strategies is possible, only when:

(a) The gains of factorisation and superposition do not overlap.

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(b) The output is concentrated in a few wave modes (δ-function).

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The extent of quantum advantage achievable is problem dependent.

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- Particle dynamics would give up superposition. Multiple paths would then be evaluated one by one. The execution time would increase.
- Wave dynamics would use N coupled oscillators, instead of $\log_2 N$ qubits. The required spatial resources would go up.

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Can we gainfully mimic such strategies?
Two coherent signal streams would be a good start.